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167 W, power scalable ytterbium-doped photonic bandgap fiber amplifier at 1178nm

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Abstract: An ytterbium-doped photonic bandgap fiber amplifier operating at the long wavelength edge of the ytterbium gain band is investigated for high power amplification. The spectral filtering effect of the photonic bandgap efficiently suppresses amplified spontaneous emission at the conventional ytterbium gain wavelengths and thus enables high power amplification at 1178 nm. A record output power of 167 W, a slope efficiency of 61% and 15 dB saturated gain at 1178 nm have been demonstrated using the ytterbium-doped photonic bandgap fiber.

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1. Introduction

Lasers and amplifiers operating in the 1150-1200 nm wavelength region have been extensively developed, typically using bulk solid-state laser technology. Frequency doubling of these wavelengths produces yellow-orange light from 570 to 600 nm – a region useful for various medical applications, high-resolution spectroscopy, and laser-guide-star facilities [1]. Ytterbium-doped fibers in general have a very broad fluorescence spectrum extending up to 1200 nm and have been thoroughly investigated for long wavelength lasers and amplifiers [2–7]. The small-signal gain per unit length can be as high as 0.8 dB/m and hence the net gain can easily exceed 10 dB at 1178 nm [8]. This is an important wavelength to access 589 nm laser-guide-star sources by frequency doubling. However, the large gain between 1030 and 1100 nm creates very strong amplified spontaneous emission (ASE) and can lead to parasitic lasing. Parasitic lasing will limit the available gain at 1178 nm and thereby the power scalability. In order to overcome the problem of parasitic lasing we propose an ytterbium-doped photonic bandgap (PBG) fiber amplifier in which an ytterbium-doped core is combined with the wavelength-filtering effect of PBG confinement. Efficient suppression of ASE at the conventional ytterbium gain wavelengths between 1030 and 1100 nm and a reduction in parasitic lasing outside the bandgap can be obtained. PBG fibers have previously been investigated for gain shaping at both short [9] and long [10,11] wavelengths as well as for lasers [12–14].

In this work, we developed an ytterbium-doped solid-core airclad PBG fiber amplifier, for which as much as 167 W of output power and a slope efficiency of 61% have been achieved at a wavelength of 1178 nm – a record output power for ytterbium-doped fiber laser and amplifiers in this wavelength region and for PBG fiber lasers and amplifiers. The output spectrum shows no sign of ASE, thus, even further power scaling can be expected. The good beam quality and the polarization-maintaining properties make this fiber amplifier very well suited for frequency doubling to 589 nm.

2. Properties of the photonic bandgap fiber

The solid-core PBG fiber fabricated for the amplifier is similar to those reported in [8,15]. The signal core consists of an ytterbium-doped rod, which is index-matched to the silica background and the core is surrounded by a PBG cladding structure composed of eight rings of high-index germanium-doped rods with a pitch of 10.1 µm. Microscope images of the fiber structure are shown in Fig. 1. In the images the lighter regions are the germanium-doped rods, while the two darker regions are boron-doped rods for inducing a birefringence on the order of 10^{-4} in the fiber. The low refractive index of the boron rods results in confinement by total internal reflection in the direction of the boron rods, while maintaining bandgap guidance in the orthogonal direction. The mode field diameter is ~10.3 µm, the pump-cladding diameter is ~220 µm, the numerical aperture of the pump cladding is 0.6, the pump absorption is ~1.1

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dB/m at 976 nm and the core loss at 1178 nm is ~0.03 dB/m. The optimal fiber length was calculated based on the pump absorption and loss measurements to ~40 m. The polarization extinction ratio in this 40 m long fiber was measured to 17 dB.

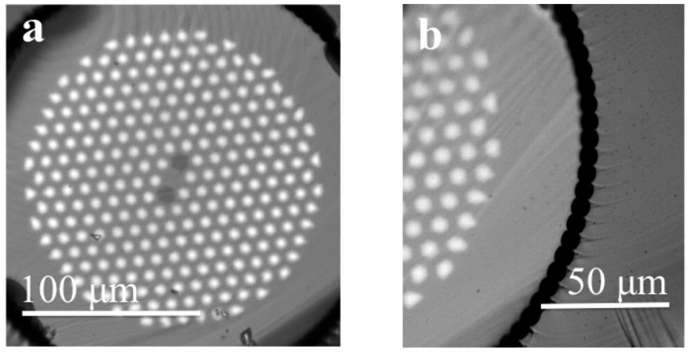

Fig. 1. Microscope images of (a) the pump-cladding structure and (b) the airclad structure surrounding the pump-cladding. The lighter regions are high-index germanium-doped rods.

3. Photonic bandgap fiber amplifier

In active PBG fibers the gain peak is moved inside the bandgap to the wavelength where the combination of material gain and bandgap loss gives the highest gain value. The effect of the photonic bandgap on the gain profile of an ytterbium-doped fiber is illustrated in Fig. 2. The calculated net small-signal gain of a 40 m-long fiber coiled to 26 cm and pumped with 275 W of 976 nm light is plotted both with and without distributed spectral filtering incorporated. The fiber parameters for the two fibers are identical except for the absence of a bandgap for the black curve. The ytterbium concentration is 0.38×10^{20} cm^{-3} and the signal-core overlap factor of 0.84. The small signal gain is ~22 dB at 1178 nm for PBG fiber at this power level.

To avoid parasitic lasing as the pump power is increased it is essential to operate the amplifier close to the wavelength of peak amplification and to ensure that the loss slope of the bandgap edge is sharp enough to cancel the steep gain slope. Thus, both the position and the steepness of the short wavelength edge of the bandgap relative to the signal gain are crucial to the efficiency of the amplifier. The position of the bandgap, and thereby the position of peak amplification, can be shifted towards longer or shorter wavelengths by rescaling the dimensions of the fiber.

Smearing of the loss slope at the bandgap edge can be caused by pitch variations along the fiber length and will impact the filtering properties significantly. Previous investigations have shown that a 0.1 µm change in pitch can lead to a change in the position of the bandgap edge of around 10 nm [16]. Therefore, pitch variations should be kept at a minimum. The uniformity of the fiber is an engineering challenge (yield and stability of the drawing tower and furnace conditions).

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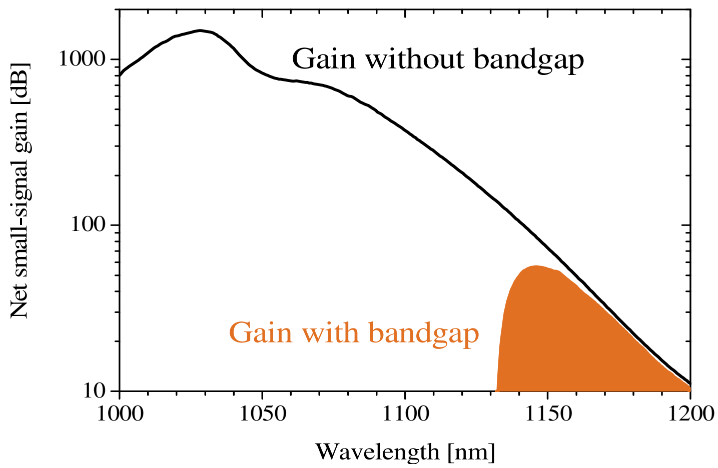

Fig. 2. Net small-signal gain of a 40 m-long ytterbium-doped fiber coiled to a diameter of 26 cm with 275 W of pump power. The black curve is the gain without distributed filtering, while the orange filled curve is the gain with distributed filtering arising from the photonic bandgap effect.

This is the reason why ASE and parasitic lasing limited the 1178 nm amplifier based on the previous fiber [8,15]. The gain of an ytterbium-doped fiber increases fast as the wavelength is decreased, and in order to obtain high-efficiency power extraction at 1178 nm, the loss slope needs to be steeper than the gain slope at wavelengths shorter than 1178 nm, combined with ultra-low loss at 1178 nm [8]. Thus, power scaling of an ytterbium-doped PBG fiber amplifier at long wavelengths is a great challenge. Compared to the fiber in [8] the current fiber has a steeper bandgap edge due to improved uniformity, achieved by screening and selecting a fiber section with reduced pitch variations along the fiber length. The improvements contribute to a far more efficient suppression of ASE and parasitic lasing. The short wavelength bandgap edge of the improved fiber is compared to that of the fiber in [8] in Fig. 3. With nearly the same loss value at 1178 nm and a difference of almost 10 nm in the position of the short-wavelength edge the newer fiber is more efficient at suppressing ASE and parasitic lasing.

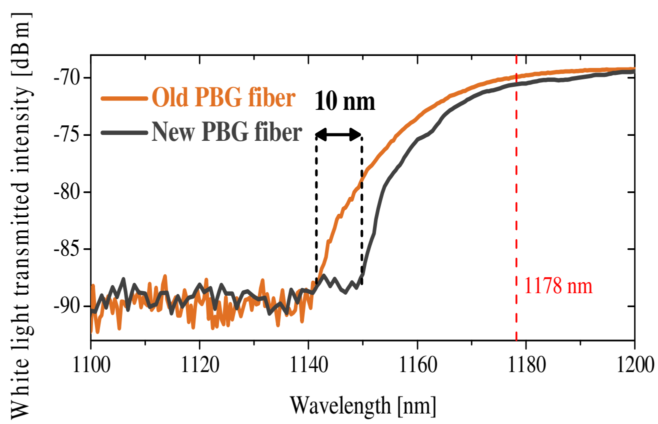

Fig. 3. Comparison of the bandgap transmission spectra between the old and the new PBG fiber. The newer fiber is fabricated with a slight change in bandgap position and with a steeper short-wavelength bandgap edge. The length of the old PBG fiber is 36 m, while the new PBG fiber is 40 m. The spectral resolution is 2 nm.

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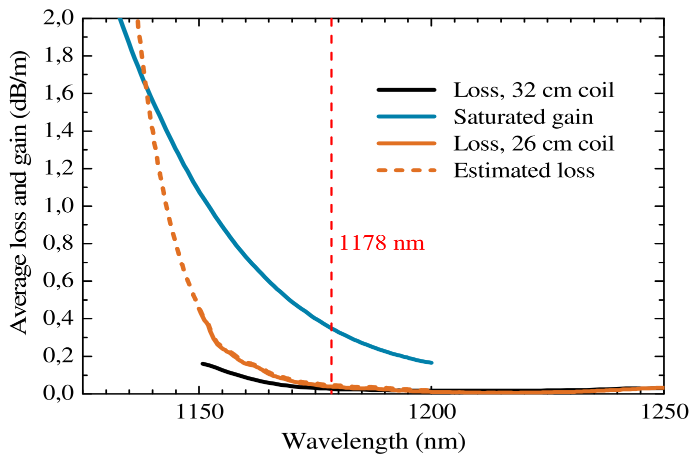

Fig. 4. The average loss curve of 40 m PBG fiber coiled to a diameter of 32 cm (black) and 26 cm (orange) compared to the average saturated gain with no bandgap, 275 W of pump power and 5 W of seed power (blue). The dashed orange curve is an estimated loss slope. Only after coiling the fiber to a diameter of 26 cm is the loss slope steep enough to cancel the gain slope.

Coiling the fiber also has a substantial effect on the bandgap [17–19]. When the fiber is coiled, core modes at the short-wavelength edge of the bandgap are resonant with radiation modes on the outside of the coil, while core modes at the long-wavelength edge are resonant with radiation modes on the inside of the coil. As a consequence the bandgap narrows. This is a characteristic property of PBG fibers and can be used to fine-tune the position of the bandgap. In addition, a steeper loss slope can be achieved by coiling. In Fig. 4 the average loss of the PBG fiber is compared to the average saturated gain with 275 W of pump power and 5 W of seed power for an ytterbium-doped fiber without an incorporated PBG structure. The loss slope of the fiber is not steep enough to cancel the gain slope at a coil diameter of 32 cm, thus eventually parasitic lasing will occur. With a tighter coil to a diameter of 26 cm the loss slope is estimated to be steeper than the gain slope and will therefore more efficiently suppress parasitic lasing.

The amplifier setup is illustrated in Fig. 5. In the experiment, the fiber was coiled to a diameter of 26 cm, and both fiber ends were sealed and angle polished by 10°, resulting in a reflection suppression on the order of 40 dB. A home-built unpolarized fiber Raman laser (FRL) at 1178 nm was used as seed source. The amplifier was seeded with ~5 W, well above the saturation power level in order to ensure gain saturation. The amplifier was backward-pumped using a 976 nm laser diode (LD, Laserline LDM200-350). At the seed input end two dichroic mirrors (HR > 1150 nm and HT < 1100 nm) are used for seed laser protection and at the signal output end a dichroic mirror (HR at 1000-1300 nm and HT at 976 nm) is used to filter out pump light in the output spectrum. The seed coupling efficiency is 50% in free space configuration, and the pump coupling efficiency is 71% due to cladding modes in the output fiber from the laser diode (~20%) and Fresnel reflection at the fiber input end.

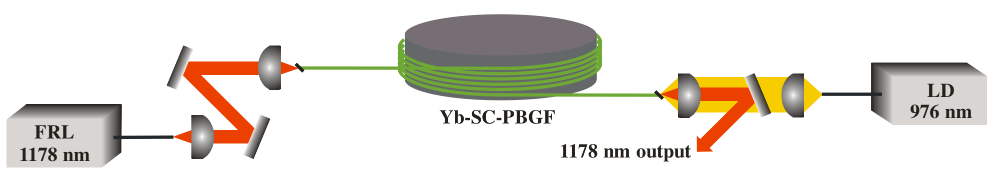

Fig. 5. Ytterbium-doped solid-core photonic bandgap fiber amplifier, seeded by an 1178 nm fiber Raman laser, and backward-pumped by a 976 nm laser diode.

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4. High power amplification at 1178 nm

From the PBG fiber amplifier we obtained an output power of 167 W with a pump power of 275 W – a record output power for an ytterbium-doped fiber amplifier in this wavelength region as well as for PBG fiber amplifiers. The maximum output power of the amplifier was limited by the available pump power. Output power as a function of launched pump power is shown in Fig. 6. The index of the germanium rods in the cladding is higher than the surrounding silica background and as a consequence a fraction of pump light will be trapped in the germanium rods and cannot be used for exciting the ytterbium ions in the core as it passes through the fiber. The slope efficiency was measured to 61%, however considering the fraction of trapped pump light, the actual slope efficiency is as high as 69%. The NA of the germanium rods is 0.2 and therefore trapping of pump light can only be reduced by avoiding pump light NAs below 0.2, e.g. by angled pump coupling or by using special combiners.

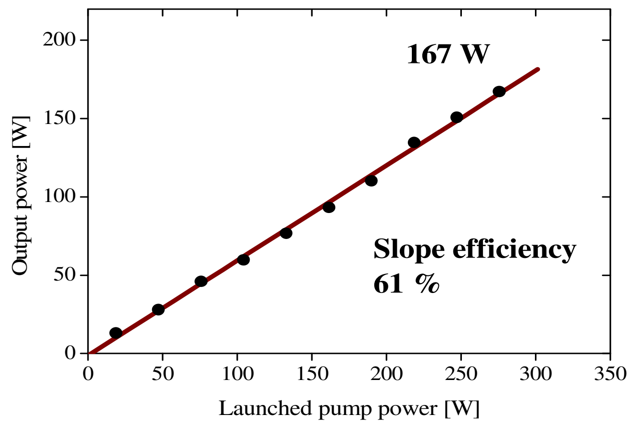

Fig. 6. Output power at 1178 nm as a function of launched pump power. The measurement was limited by available pump power, and the output spectrum showed no sign of amplified spontaneous emission, thus the power is scalable.

The output spectrum of the amplifier in Fig. 7 shows pump power limited on/off amplification of up to 16 dB. Considering amplification of coupled seed power rather than transmitted seed power, the actual gain in the amplifier is 15 dB. The linewidth before and after amplification is 1.3 nm. A nearly complete absence of ASE in the output spectrum suggests that further power scaling can be expected. The fiber is expected to reach the parasitic lasing limit at around 17 dB, limiting the current system to ~250 W with 5 W of seed power. However, further power scaling can be achieve e.g. by including an additional amplifier stage. An M^2 measurement has been performed with an output power of 100 W and yields a value of ~1.1, indicating that the amplifier produces a single-mode output. Figure 8 shows the near field image at 100 W. The mode field diameter is ~10.3 µm.

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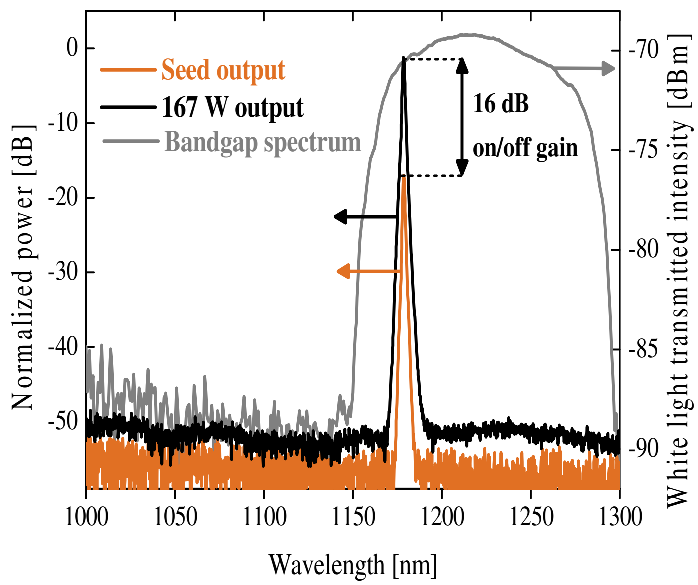

Fig. 7. Amplifier output spectra of the seed (red) and the 167 W output (black). The bandgap position and shape (grey) is crucial to the efficiency of the amplifier. The spectral resolution of the output spectra is 0.5 nm and the linewidth before and after amplification is 1.3 nm.

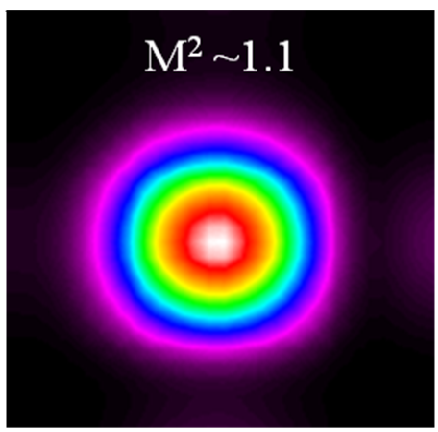

Fig. 8. Near field image at an output power of 100 W. The output has an M^2 value of ~1.1 and a mode field diameter of ~10.3 µm.

New amplification experiments with the fiber from [8] resulted in very high power as well, however, the output was limited by parasitic lasing at 91 W. A comparison between these two fibers indicates that even though scalability to very high power depends strongly on the exact bandgap shape and position, still quite high powers can be extracted from fibers with less than optimum bandgap shape and position.

Furthermore, frequency doubling to 589 nm has been achieved using the PBG fiber amplifier combined with a narrowband seed laser – the results will be reported elsewhere [20].

5. Conclusion

We have demonstrated a record output power of 167 W at 1178 nm and a slope efficiency of 61% using a polarization-maintaining ytterbium-doped solid-core photonic bandgap fiber

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amplifier. The results obtained with this amplifier are, to our knowledge, the highest output powers generated from ytterbium fiber lasers and amplifiers at these long wavelengths and from PBG fibers lasers and amplifiers. Furthermore, since the output spectrum is free of ASE, scaling to even higher powers is possible in this fiber amplifier. We have demonstrated the importance of exact positioning and shaping of the bandgap for optimum engineering of the ytterbium gain band. In addition, an older PBG fiber in which the output power at 1178 nm was limited by parasitic lasing due to a less suitable bandgap shape still reached power levels far above what has been achieved in other fiber lasers and amplifiers at this wavelength. The good beam quality and polarization characteristics make the amplifier suitable for frequency conversion to the yellow-orange.

The PBG fiber amplifier concept has shown itself very promising for high power applications and can easily be extended to other wavelengths in the ytterbium gain region, even as high as 50% conversion efficiency can be expected at 1200 nm [21]. Furthermore, gain profiling by the PBG technique can also be extended to other rare earth doped fibers.

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